(49) 圧縮力を受けるCFT柱におけるSRC規準とユーロコード4の設計式の比較

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The purpose of this paper is to make a comparison of design equations for CFT compressive members between SRC Standards and Eurocode 4. The design equations for CFT compressive members based on SRC Standards and Eurocode 4 are presented. The width-to-thickness ratio, the strength of steel and the strength of concrete are the parameters to make a comparison for the ultimate strength calculated by these two different standards.

Key Words : *CFT columns, ultimate strength, relative slenderness, effect of confinement*

1. INTRODUCTION

In Japan, there are two standards for the design of CFT structures by Architectural Institute of Japan (AIJ). The one is AIJ Standard for Structural Calculation of Steel Reinforced Concrete Structures[1)] (from now on referred to as SRC Standards), the other one is Recommendations for Design and Construction of Concrete Filled Steel Tubular Structures[2)] (referred to as Recommendations for CFT). There are also some guidelines for CFT published by Association of New Urban Housing Technology[e.g.3)]. Besides Japan, several standards or codes for design of steel-concrete structures have been applied, such as AISC Standards standardized by American Institute of Steel Construction, ACI Standards standardized by American Institute of Concrete and Eurocode standardized by European Committee for Standardization. In reference 4) and 5), design equations for CFT Structures of China, the United States and Europe have been shown and the strength of CFT column obtained by these equations were compared, however, the number of parameters was relatively small. In Japan, a lot of buildings with composite structure were constructed according to the standards and guidelines. In recent years, composite structure and the demand performance of composite structure have been diversified. Furthermore, the contents of design standards in the United States, Europe and China have been developed[6)]. Because of these situations, future standard for composite structure have been discussed [6)～8)]. In reference 6)， design standards in overseas were presented. It is helpful to show the difference between Japanese standards and other countries standards when we discuss the future standard for composite structures in Japan.

The purpose of this paper is to make comparison between SRC Standards in Japan and Eurocode 4[9)] about the design equations for CFT compressive members as a basic study. The design equations for CFT compressive members in SRC Standards and Eurocode 4 are presented. The width-to-thickness ratio, the strength of steel and the strength of concrete are the parameters to make a comparison for the ultimate strength calculated by these two different standards.

2. DESIGN EQUATIONS OF CFT MEMBERS

(1) Design equations based on SRC Standards

(a) Ultimate compressive strength of a CFT column

The design equations for ultimate compressive strength of CFT members are shown as follows.

$$l_k / D \leq 4; \quad N_{cU1} = {}_cN_{cU} + (1+\eta)\,{}_sN_{cU} \tag{1}$$

$$4 < l_k / D \leq 12;$$
$$N_{cU2} = N_{cU1} - 0.125(N_{cU1} - N_{cU3})(\frac{l_k}{D} - 4) \tag{2}$$

$$12 < l_k / D; \quad N_{cU3} = {}_cN_{cr} + {}_sN_{cr} \tag{3}$$

where, l_k is effective length of a CFT column, D is width or diameter of a steel tube section. η is the coefficient of confining effect of the steel tube to concrete.

$$\eta = \begin{cases} 0 & \text{: square cross-section} \\ 0.27 & \text{: circular cross-section} \end{cases} \tag{4}$$

N_{cU3} in Eq.(2) is calculated by Eq. (3) on the condition that l_k/D=12.

(b) Ultimate strength and buckling strength of a concrete column

${}_cN_{cU}$ is the ultimate strength of concrete column which is calculated by Eq. (5), and ${}_cN_{cr}$ is the buckling strength of concrete column defined by Eq. (6).

$${}_cN_{cU} = {}_cA \cdot {}_cr_U \cdot F_c \tag{5}$$

where: ${}_cA$ is the area of concrete; F_c is the design standard strength of concrete; ${}_cr_U$ is the reduction factor for concrete.

For SRC Standards, the factor is equal to 0.85[1], while the value of ${}_cr_U$ equals 1.0 in Recommendations for CFT[2]. In this paper, the coefficient is equal to 1.0.

The buckling strength of concrete column ${}_cN_{cr}$ is calculated by the equation shown as follows.

$${}_cN_{cr} = {}_cA \cdot {}_c\sigma_{cr} \tag{6}$$

$${}_c\sigma_{cr} = \begin{cases} \dfrac{2}{1+\sqrt{{}_c\lambda_1^4 + 1}}\,{}_c\sigma_B & \text{for } {}_c\lambda_1 \leq 1.0 \\ 0.83\exp\{C_c(1 - {}_c\lambda_1)\}\,{}_c\sigma_B & \text{for } {}_c\lambda_1 \geq 1.0 \end{cases} \tag{7}$$

where: ${}_c\sigma_{cr}$ is the critical stress of concrete column; ${}_c\sigma_B$ is the compressive stress of concrete which is calculated by Eq. (8); C_c is the coefficient of buckling strength of CFT column defined by Eq. (9); ${}_c\lambda_1$ is the normalized slenderness ratio of concrete column calculated by Eq. (10).

$${}_c\sigma_B = {}_cr_U \cdot F_c \tag{8}$$

$$C_c = 0.568 + 0.00612 F_c \tag{9}$$

$${}_c\lambda_1 = \frac{{}_c\lambda}{\pi}\sqrt{{}_c\varepsilon_U} \tag{10}$$

In Eq. (10), ${}_c\lambda$ is the slenderness ratio of concrete column; ${}_c\varepsilon_U$ is the strain of concrete corresponding to relative compressive stress defined by Eq. (11).

$${}_c\varepsilon_U = 0.93 \cdot {}_c\sigma_B^{1/4} \cdot 10^{-3} \tag{11}$$

(c) Ultimate strength and buckling strength of a steel tube column

${}_sN_{cU}$ is the ultimate strength of steel tube which is calculated by Eq. (12), and ${}_sN_{cr}$ is the buckling strength of steel tube column determined by Eq. (13).

$${}_sN_{cU} = {}_sA \cdot F \tag{12}$$

Where: ${}_sA$ is the area of steel tube; F is the reference design standard strength of steel tube.

Based on Recommendations for the Plastic State Design of Steel Structures[10], ${}_sN_{cr}$ should be calculated by Eq. (13).

$$\left.\begin{array}{ll} \text{when } {}_s\lambda_1 < 0.3 & {}_sN_{cr} = {}_sN_Y \\ \text{when } 0.3 \leq {}_s\lambda_1 < 1.3 & {}_sN_{cr} = \{1 - 0.545({}_s\lambda_1 - 0.3)\}\,{}_sN_Y \\ \text{when } {}_s\lambda_1 \geq 1.3 & {}_sN_{cr} = \dfrac{{}_sN_E}{1.3} \end{array}\right\} \tag{13}$$

where: ${}_sN_Y$ is the yielding axial force of steel tube (${}_sN_Y = {}_sA \cdot F$); ${}_s\lambda_1$ is the normalized slenderness ratio of steel tube calculated by Eq. (14). ${}_sN_E$ is the elastic buckling force of steel tube.

$${}_s\lambda_1 = \frac{{}_s\lambda}{\pi}\sqrt{\frac{F}{{}_sE}} \tag{14}$$

where: ${}_sE$ is the modulus of elasticity of steel tube; ${}_s\lambda$ is the slenderness ratio of steel tube.

(2) Design equations based on Eurocode 4

In this paper, the influence of long-term effect and member imperfections are not taken into account. The method of design about composite cross-section by Eurocode 4 is shown as follows.

(a) Plastic resistance to compression of general composite cross-section

The plastic resistance to compression $N_{pl,Rd}$ of a composite cross-section should be calculated by adding the plastic resistances of its components.

$$N_{pl,Rd} = A_a f_{yd} + 0.85 A_c f_{cd} + A_s f_{sd} \tag{15}$$

where: A_a, A_c and A_s are the cross-sectional areas of the structural steel section, the concrete section and the reinforcement; f_{yd}, f_{cd} and f_{sd} are the design value of the yield strength of structural steel, the cylinder compressive strength of concrete and the yield strength of reinforcing steel.

For concrete filled sections, the coefficient 0.85 may be replaced by 1.0 in Eq. (15).

(b) Plastic resistance to compression of circular CFT

For concrete filled tubes of circular cross-section, account may be taken of increase in strength of concrete caused by confinement provided that the relative slenderness $\bar{\lambda}$ defined in Eq. (19) doesn't exceed 0.5 and e/d < 0.1, where, e is the eccentricity of loading and d is the external diameter of the column. The plastic resistance to compression may then be calculated from the following expression:

$$N_{pl,Rd} = \eta_a A_a f_{yd} + A_c f_{cd}\left(1+\eta_c \frac{t}{d}\frac{f_y}{f_{ck}}\right) + A_s f_{sd} \tag{16}$$

where: t is the wall thickness of the steel tube; f_y is the nominal value of the yield strength of structural steel; f_{ck} is the characteristic value of the cylinder compressive strength of concrete at 28 days.

For members with e = 0 the values $\eta_a = \eta_{a0}$ and $\eta_c = \eta_{c0}$ are given by the following expressions:

$$\eta_{a0} = 0.25\left(3+2\bar{\lambda}\right) \qquad (\text{but} \le 1.0) \tag{17}$$

$$\eta_{c0} = 4.9 - 18.5\bar{\lambda} + 17\bar{\lambda}^2 \qquad (\text{but} \ge 0) \tag{18}$$

(c) Relative slenderness, steel contribution ratio and design value of compressive normal force

The relative slenderness for the plane of bending being considered is given by:

$$\bar{\lambda} = \sqrt{\frac{N_{pl,Rk}}{N_{cr}}} \quad \text{and} \quad \bar{\lambda} \le 2.0 \tag{19}$$

where: $N_{pl,Rk}$ is the characteristic value of the plastic resistance to compression given by Eq.(15) if, instead of the design strengths, the characteristic values are used; N_{cr} is the elastic critical normal force for the relevant buckling mode, calculated with effective flexural stiffness determined in accordance with Eq. (20).

For the determination of the relative slenderness $\bar{\lambda}$ and the elastic critical force N_{cr}, the characteristic value of the effective flexural stiffness $(EI)_{eff}$ of a cross-section of a composite column should be calculated from:

$$(EI)_{eff} = E_a I_a + E_s I_s + K_e E_{cm} I_c \tag{20}$$

where: K_e is a correction factor that should be taken as 0.6. I_a, I_c and I_s are the second moments of area of the structural steel section, the un-cracked concrete section and the reinforcement for the bending plane being considered. E_a is the modulus of elasticity of structural steel; E_s is the design value of modulus of elasticity of reinforcing steel; E_{cm} is the secant modulus of elasticity of concrete calculated by Eurocode 2[11)].

The steel contribution ratio is defined as:

$$\delta = \frac{A_a f_{yd}}{N_{pl,Rd}} \quad \text{and} \quad 0.2 \le \delta \le 0.9 \tag{21}$$

where: $N_{pl,Rd}$ is the plastic resistance to compression defined in Eq. (15).

(d) Resistance of members in axial compression

For simplification for members in axial compression, the design value of the normal force N_{Ed} should satisfy:

$$\frac{N_{Ed}}{\chi N_{pl,Rd}} \le 1.0 \tag{22}$$

Where: $N_{pl,Rd}$ is the plastic resistance of the composite section according to Eq. (15), but with f_{yd} determined using the partial factor γ_{M1}=1.00 given by Eurocode 3[12)]; χ is the reduction factor for the relevant buckling mode given in Eurocode 3, in terms of the relative slenderness $\bar{\lambda}$.

The buckling curves obtained by Eurocode 3 are shown in **Fig. 1**. There are five kinds of the curves that are named as a_0, a, b, c and d respectively. The selection of buckling curve depends on the components and the characteristic of cross-section. For Eurocode 4, both CFT of square cross-section and circular cross-section are calculated by buckling curve a.

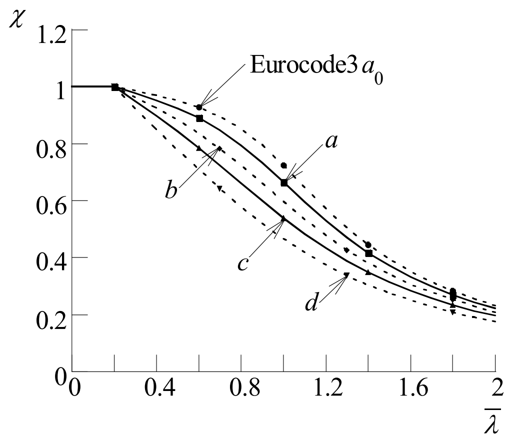


Fig. 1 Buckling curves in Eurocode 3[12)]

3. COMPARISON OF ULTIMATE STRENGTH BETWEEN SRC STANDARDS AND EUROCODE 4

(1) Conditions of analysis

Loading condition and sizes of cross-sections are presented as **Fig. 2**. The eccentricity of loading e is equal to zero. Other data for analysis are shown as follows:

$$\frac{l_k}{D} = 1 \sim 50$$
$$F_c = f_{cd} = f_{ck} = 21\text{N/mm}^2$$
$$F = f_{yd} = f_y = 325\text{N/mm}^2$$

When confining effect is considered, the value of $N_{pl,Rk}$ in Eq. (19) which is used to determine the relative slenderness $\bar{\lambda}$ is calculated by Eq. (15) in order to avoid an iterative process.

(2) Comparison of the relation between ultimate compressive strength and l_k/D

Fig. 3 shows the relation between the ratio of l_k/D and the ultimate compressive strength N_u.

Fig. 3(a) is about square cross-section whose size is shown as Fig. 2. The curve of SRC Standards is the most similar to the curve calculated by the buckling curve a in Eurocode 4. However, when the ratio of l_k/D is between 19 and 29, the curve obtained by buckling curve b is closer than others.

Fig. 3(b) is the condition of circular cross-section. The ultimate strength with confining effect is larger than that in general condition, both SRC Standards and Eurocode 4. As this figure shown, the curve by Eurocode 4 increases as the value of l_k/D decreases, while the ultimate strength by SRC Standards is constant when the l_k/D is smaller than four. The maximum ultimate value obtained by Eurocode 4 is about 1.24 times of that gotten by SRC Standards when the confining effect is considered. This is because the relative slenderness is calculated by using the $N_{pl,Rd}$ in Eq.(15).

Fig. 4 is about the circular cross-section with confining effect calculated by SRC Standards and Eurocode 4 with buckling curve a. When the value of $\bar{\lambda}$ is smaller than about 0.24, the value of N_u obtained by Eurocode 4 is much larger than that gotten by SRC Standards. When the value of $\bar{\lambda}$ is larger than 0.24, the value of N_u obtained by Eurocode 4 becomes smaller than the value gotten by SRC Standards.

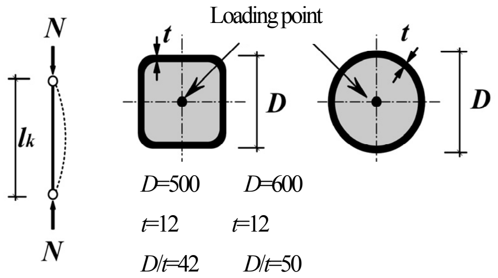


Fig. 2 Loading condition and sizes of cross-sections

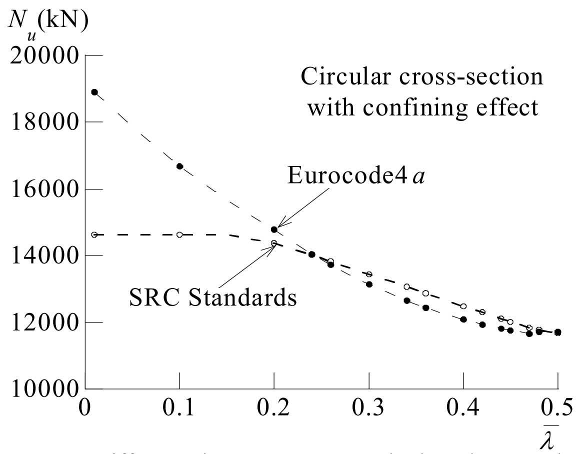
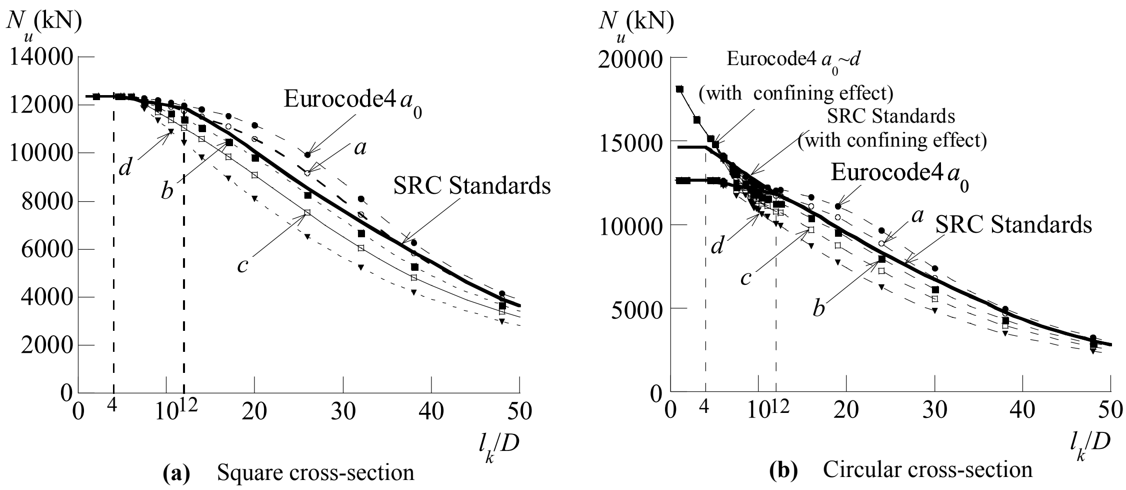


Fig. 4 Difference between SRC Standards and Eurocode 4 when the confining effect is considered



(a) Square cross-section

(b) Circular cross-section

Fig. 3 Relation between l_k / D and ultimate strength N_u

(3) Comparison by the width-to-thickness ratio *D/t*

About the width-to-thickness ratio of cross-section, the maximum value is determined by each standard. **Table 1** shows maximum width-to-thickness ratio of steel tube column limited by AIJ Design Standard for Steel Structures[13], while **Table 2** is the limit of width-to-thickness ratio for composite cross-section by Eurocode 4[9]. As analytical parameter, the width-to-thickness ratio is less than the value in **Table 3** in order to simplify the comparison. Because in Eurocode 4 the effect of local buckling of the steel section can be neglected when the value of width-to-thickness ratio do not exceed the value in Table 2.

Table 3 presents the maximum width-to-thickness ratio of the examples shown in Fig. 2 calculated by Table 1 and Table 2. It should be mentioned, when the steel tube is a component of CFT column, the maximum width-to-thickness ratio may be 1.5 times of the value obtained by Table 1. The maximum width-to-thickness ratio obtained by SRC Standards is larger than that gotten by Eurocode 4, especially of circular cross-section.

Fig. 5 presents the ratio of ultimate strength (*a*/SRC) with confining effect between Eurocode 4(calculated by buckling curve *a*) and SRC Standards as the ratio of l_k/D is changed.

Fig. 5(a) shows the condition of circular cross-section. Generally speaking, the ratio of *a*/SRC is almost larger than unity, that is to say, the value of ultimate strength gotten by Eurocode 4 is almost larger than that obtained by SRC Standards, especially when the ratio of l_k/D is less than 4. On other hand, the ratio of ultimate strength calculated by these two standards becomes larger as the width-to-thickness ratio gets smaller when l_k/D is from 40 to 50.

Fig. 5(b) is about the square cross-section with different width-to-thickness ratios. As with Fig. 5(a), the value of ultimate strength gotten by Eurocode 4 is almost larger than that obtained by SRC Standards, and the value of *a*/SRC with smaller width-to-thickness ratio is larger than that with larger ones.

According to these figures, ultimate compressive

Table 1 Maximum width-to-thickness ratio of steel tube limited byAIJ [13)]

Cross-section	Maximum value of width-to-thickness
Circular cross-section	$\max(d/t) = 0.114\dfrac{E}{F}$
Square cross-section	$\max(h/t) = 1.6\sqrt{\dfrac{E}{F}}$

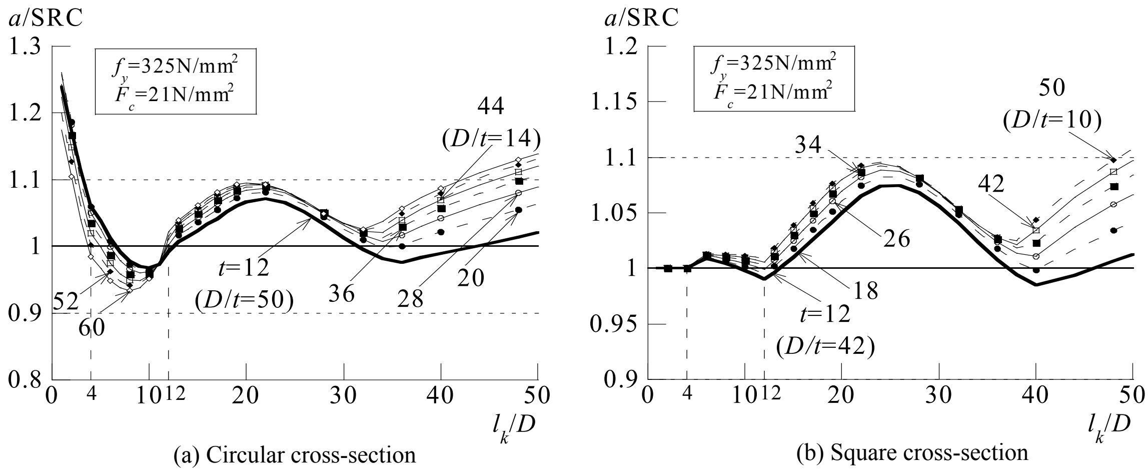
Note: when the steel tube is a part of the CFT column, the maximum width-to-thickness ratio may be 1.5 times of the value

Table 2 Maximum width-to-thickness ratio of composite cross-section limited by Eurocode 4[9)]

Cross-section	Maximum value of width-to-thickness
Circular cross-section	$\max(d/t) = 90\dfrac{235}{f_y}$
Square cross-section	$\max(h/t) = 52\sqrt{\dfrac{235}{f_y}}$

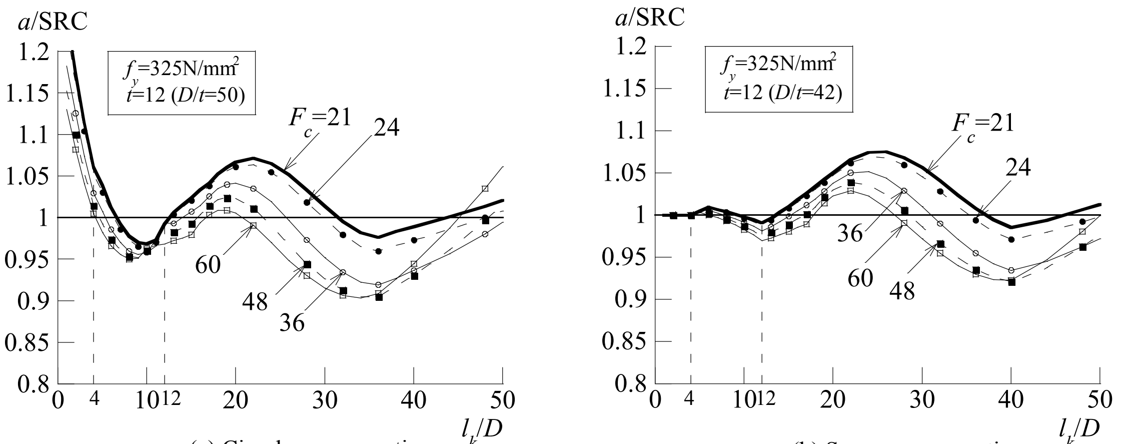
Table 3 Maximum width-to-thickness ratio of the examples shown in Fig. 2

Cross-section	Maximum value of width-to-thickness	
	AIJ	Eurocode 4
Circular cross-section	108	65.1
Square cross-section	60.3	44.2



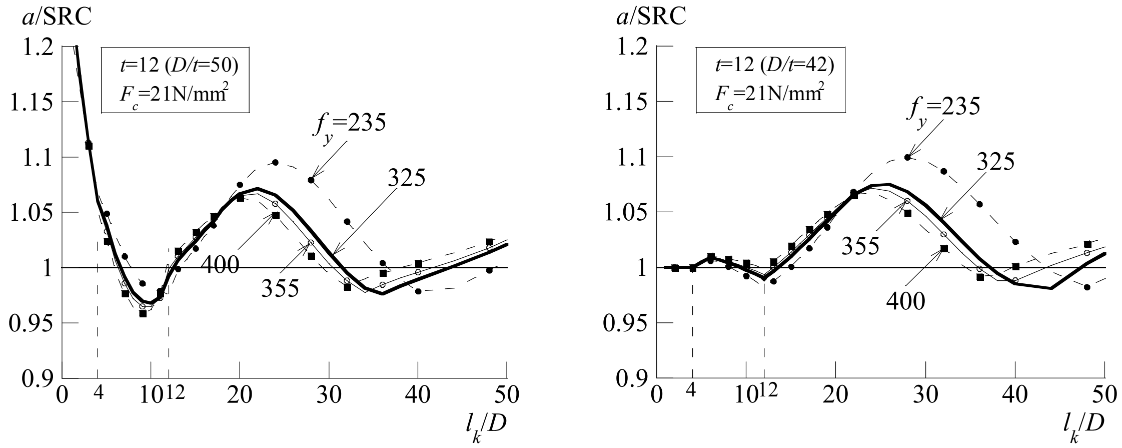
(a) Circular cross-section (b) Square cross-section

Fig. 5 Comparison with different width-to-thickness ratios *D/t*



(a) Circular cross-section (b) Square cross-section

Fig. 6 Comparison with different design standard value of concrete F_c



(a) Circular cross-section (b) Square cross-section

Fig. 7 Comparison with different yield strength of steel f_y

strengths obtained by these two standards are almost same and deviation is kept in ±10% except the circular cross-sections when l_k/D is less than 4.

(4) Comparison by strength of concrete F_c

Fig. 6 shows the relation between the ratio of a/SRC and the ratio of l_k/D as the strength of concrete is changed. Fig. 6(a) and (b) are about the conditions of circular and square cross-sections respectively.

As **Fig. 6(a)** shown, the ratio of a/SRC becomes larger as the strength of concrete decreases when l_k/D is from 12 to 30. According to the curve of F_c=21, when l_k/D is smaller than 6, the ratio of a/SRC is always larger than unity; when l_k/D is between 7 and 12, the ultimate compressive strength of SRC Standards is larger than that of Eurocode 4.

As similar with Fig. 6(a), the ratio of a/SRC in Fig. 6(b) becomes larger as the strength of concrete decreases when l_k/D is from 4 to 30. In **Fig. 6(b)**, when the ratio of l_k/D is smaller than 4, the ratio of l_k/D is equal to unity whatever the value of F_c is. According to the curve of F_c=21, the ratio of a/SRC is almost larger than unity. The maximum of a/SRC is equal to 1.07 when the ratio of l_k/D equals 26.

(5) Comparison by strength of steel tube f_y

Fig. 7 shows the relation between the ratio of a/SRC and the ratio of l_k/D as the strength of steel is changed. Fig. 7(a) and (b) are about the conditions of circular and square cross-sections respectively.

According to **Fig. 7(a)**, the shapes of curve are almost same with different strength of steel tube, except when the strength of steel tube f_y=235N/mm^2. In general, the value of ultimate strength gotten by Eurocode 4 is almost larger than that obtained by SRC Standards.

As **Fig. 7(b)** shown, the value of ultimate strength gotten by Eurocode 4 is almost larger than that obtained by SRC Standards. The ratio of a/SRC approximates unity when the ratio of l_k/D is smaller than about 15. When the ratio of l_k/D is over 15, the variation of curves is similar with Fig. 7(a).

4. **CONCLUSIONS**

In this paper, the comparison between SRC Standards and Eurocode 4 about the ultimate strength of the compressive member has been presented. By comparing these two different standards, we can get some findings shown as follows:

1. SRC Standards calculate the ultimate compressive strength of CFT members by adding the ultimate strengths or buckling strength of steel tube and concrete column, while Eurocode 4 determines the design value of compressive members by multiplying the plastic resistance $N_{\mathrm{pl,Rd}}$ by the reduction factor χ. However, the reduction factor χ is determined by the buckling curves in Eurocode 3. And both of these two standards consider the effect of confinement for circular cross-sections.
2. The ultimate compressive strengths are calculated and compared by width-to-thickness ratio, concrete strength and steel yield strength. According to the results, ultimate compressive strengths obtained by these two standards are almost same and deviation is kept in $\pm 10\%$ except the circular cross-sections when l_k/D is less than 4.

It is considered that comparing between Japanese standard and foreign standard and showing differences are helpful for discussing the future standard of composite structures. This study is a basic study about the compressive CFT members. It is expected that design equations and standards of other composite structures will compare in the future.

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